ARUP

Foundation Ex 2019
Explore innovation. Exchange ideas. Expand minds
1st October, Bristol

SHAPE A BETTER WORLD

FE analysis of monopiles – advanced modelling of soil structure interaction

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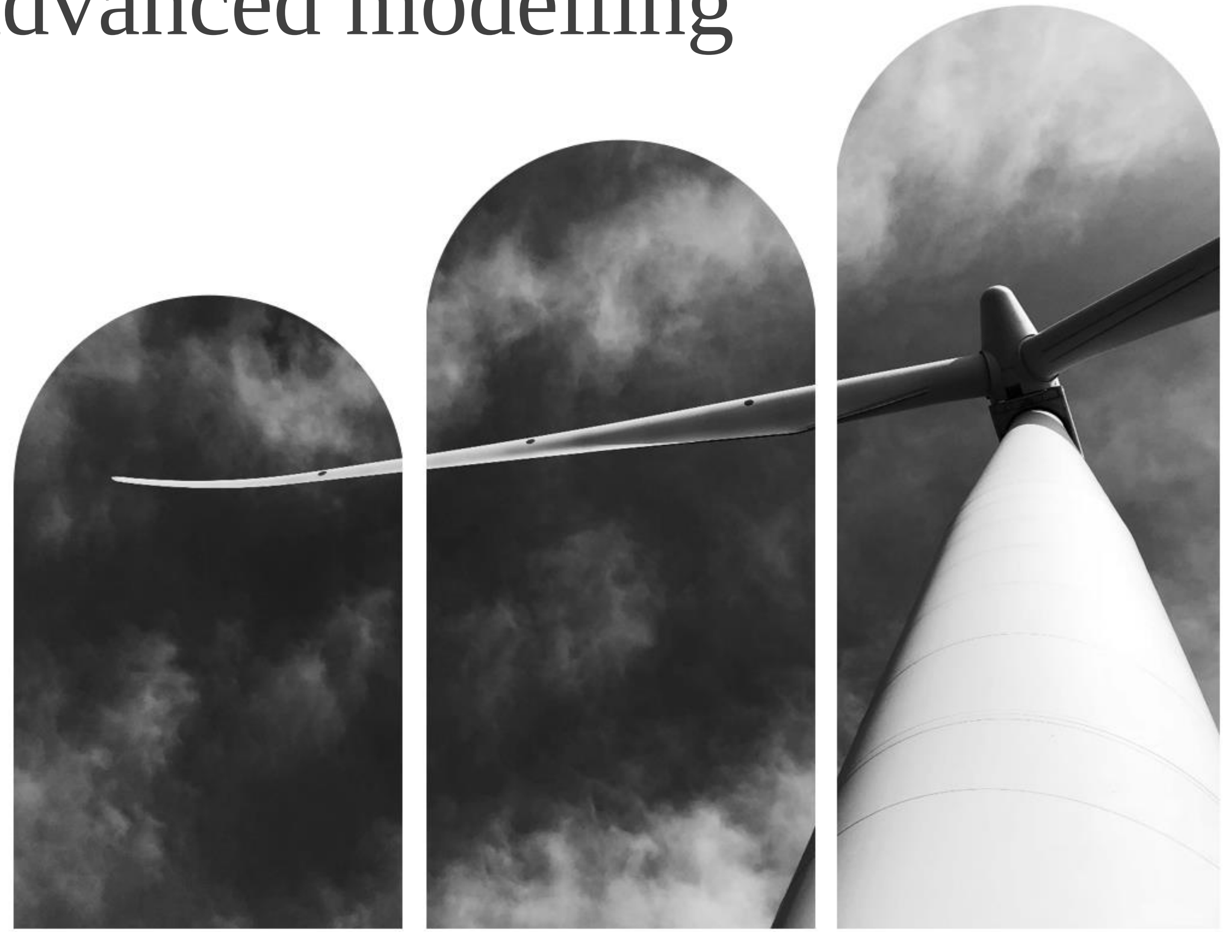

Foundation Ex Conference
1 October 2019

Contents

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2. FE analysis to optimise monopiles
3. Geotechnical modelling of pore pressure build up around monopiles under cyclic loading.
4. Design considerations for monopiles in seismic regions

ACHIEVING CLEAN RENEWABLE ENERGY CONSISTENT WITH THE UN SUSTAINABLE DEVELOPMENT GOALS

What's needed for detailed design?

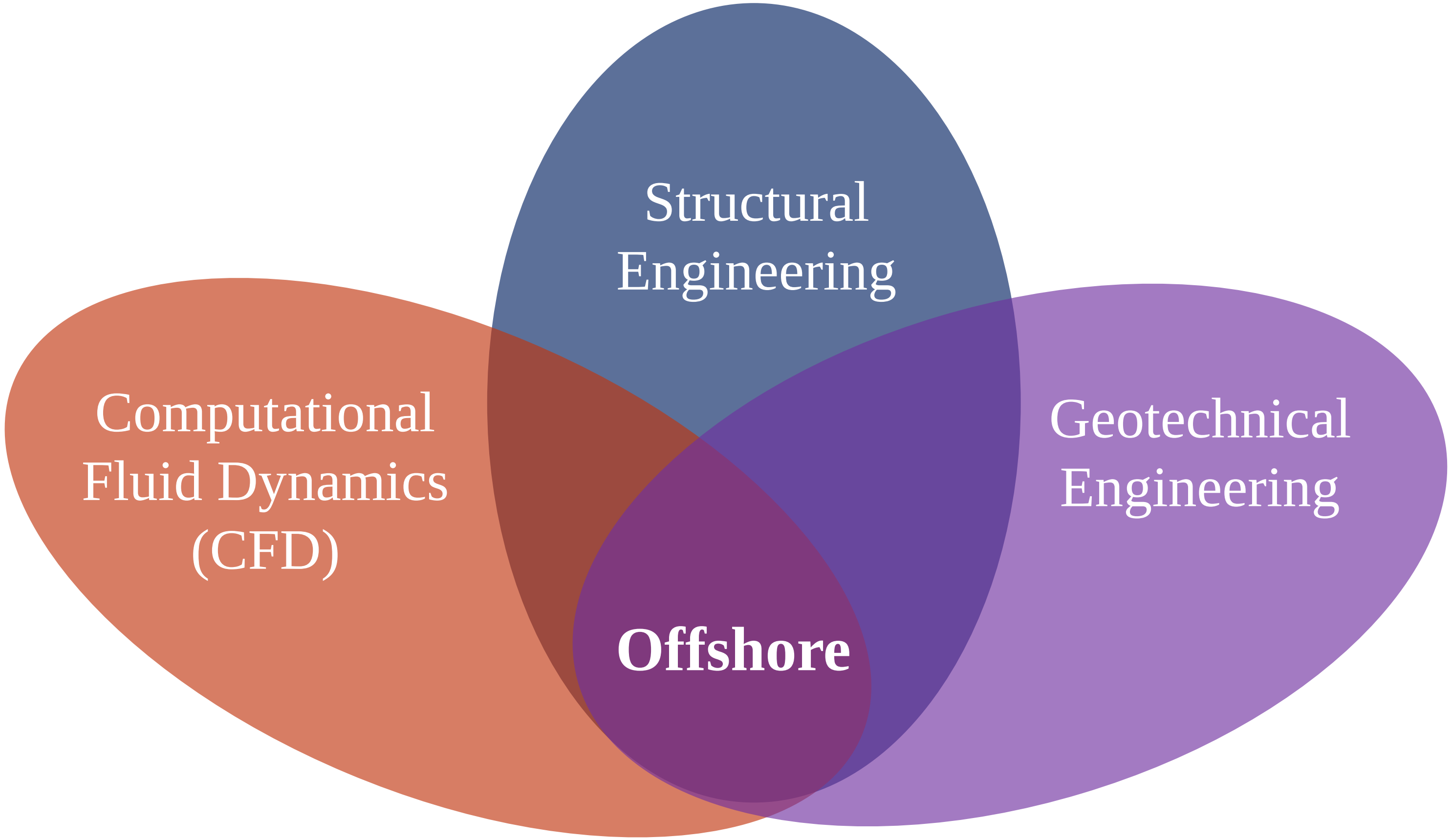
Broad & Deep Industry **Experience**
Feedback loops

Strong Relevant **Track Record**
Automate
Simplify
Optimise

Tailor-Made Teams Integrated understanding between disciplines and holistic approach

Seamless Integrated Approach
OEMs
Installers
Designers
Developers
Certifiers

Offshore Wind Engineering

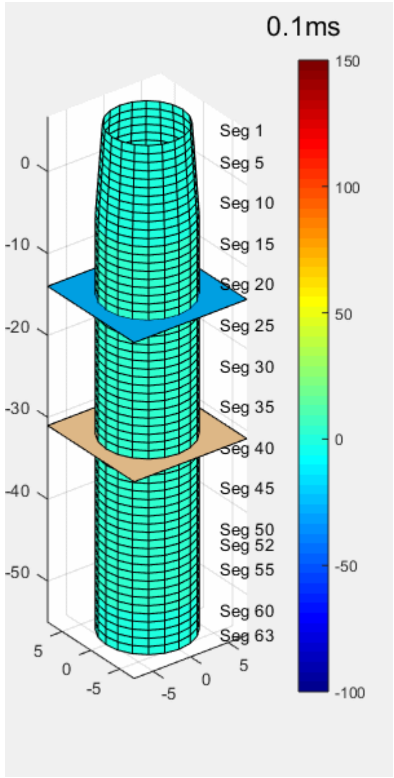


Finite element analysis to optimise monopiles

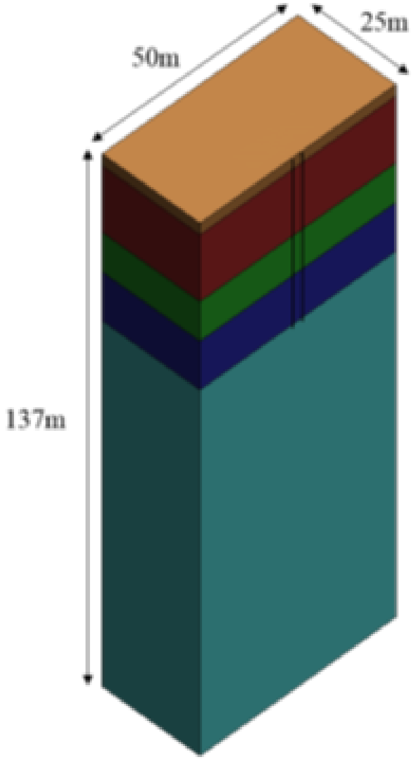
NUMEROUS APPLICATIONS

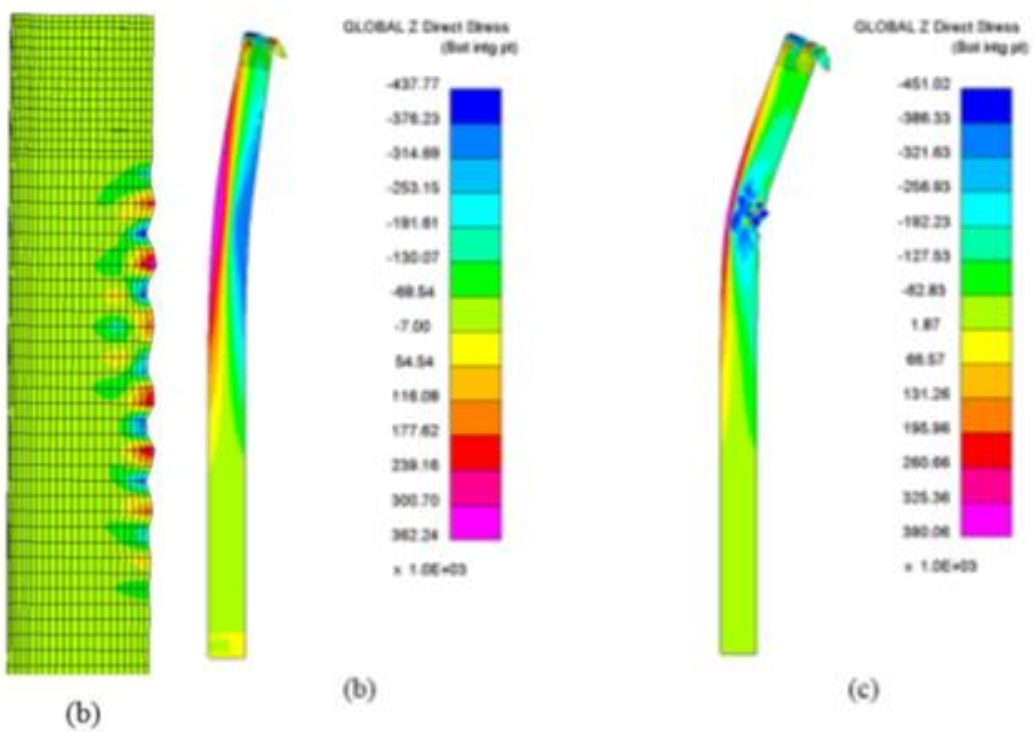
Enabling high D/t ratios through advanced, automated installation and in-service buckling analysis using non-linear FE

Pile driveability studies

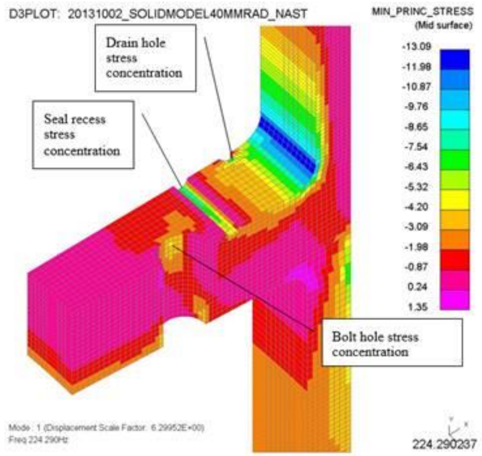


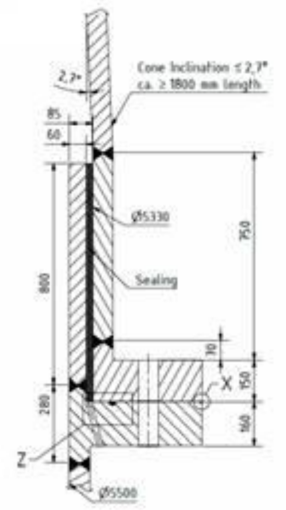
Pile Buckling

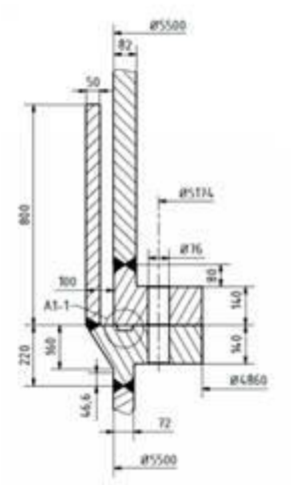


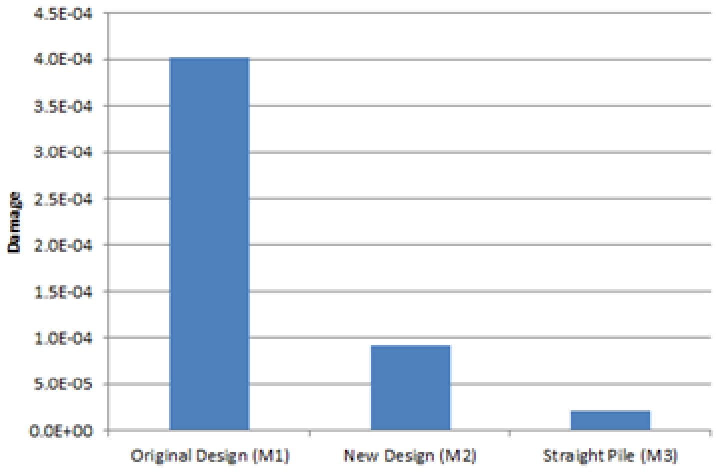


FE analysis of driving installation scenarios

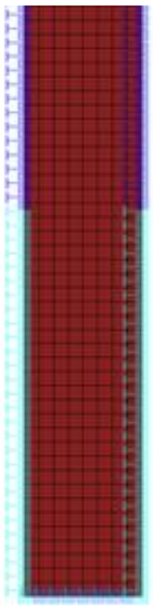


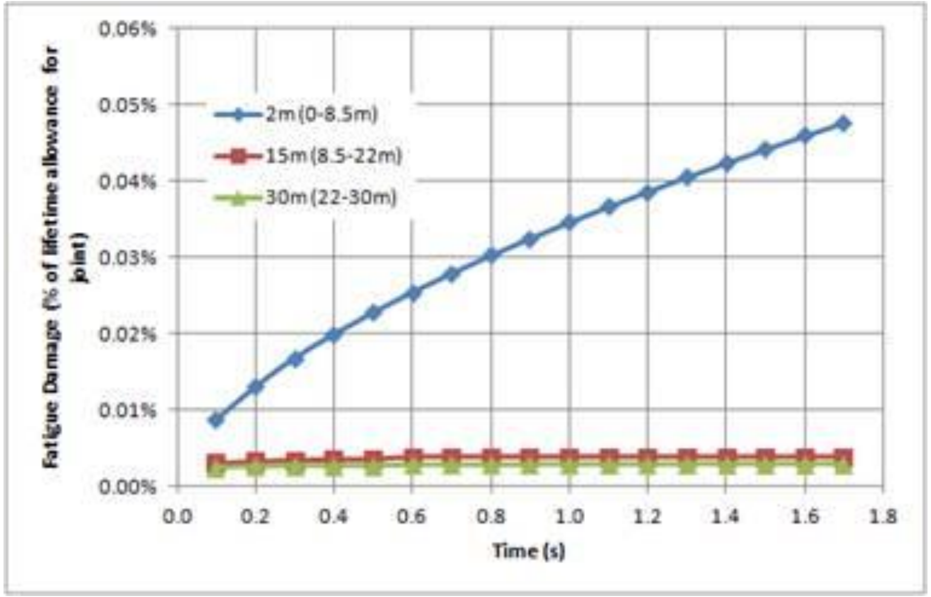


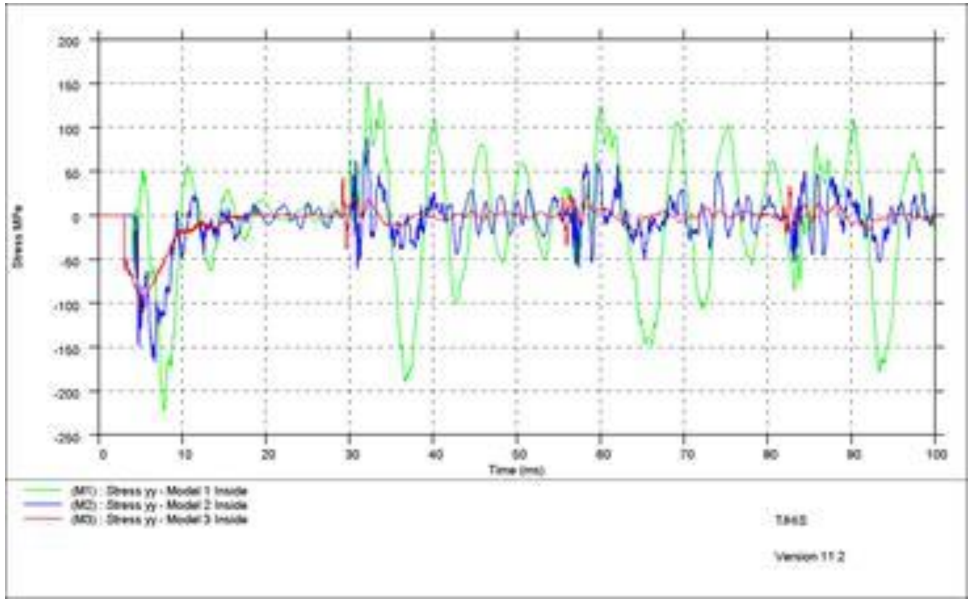




FE analysis of driving installation scenarios







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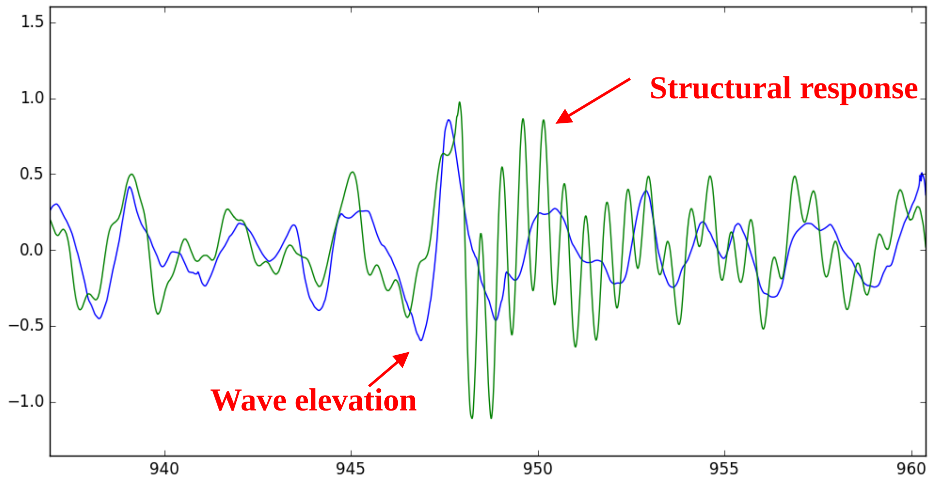
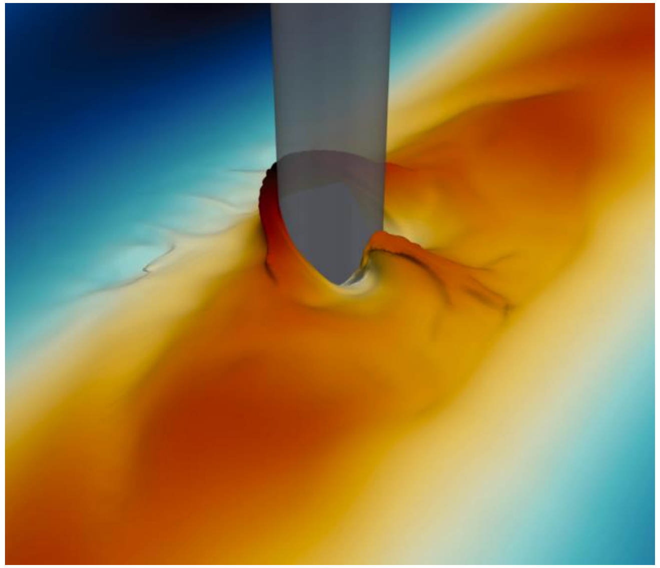
Ringing assessment during detailed design

Base moment time history

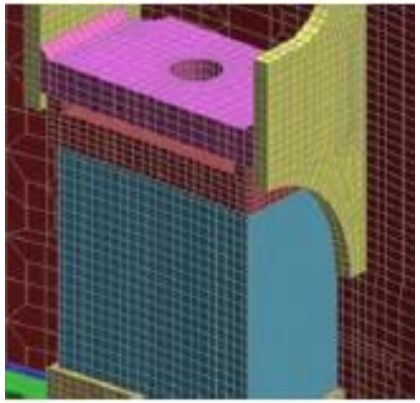


Wave structure analysis

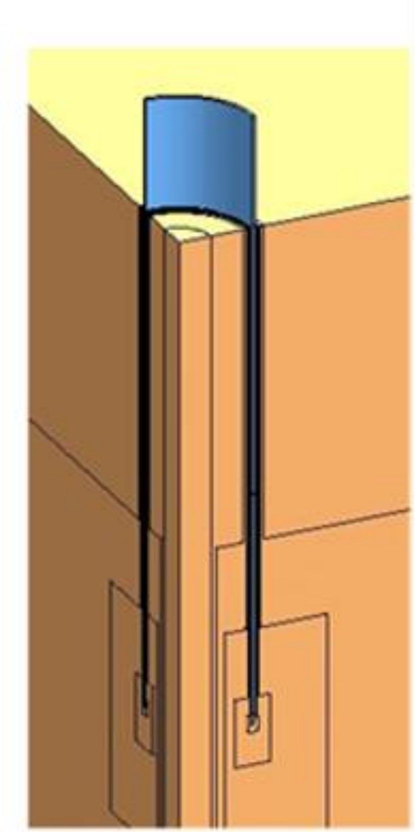


Other FE applications

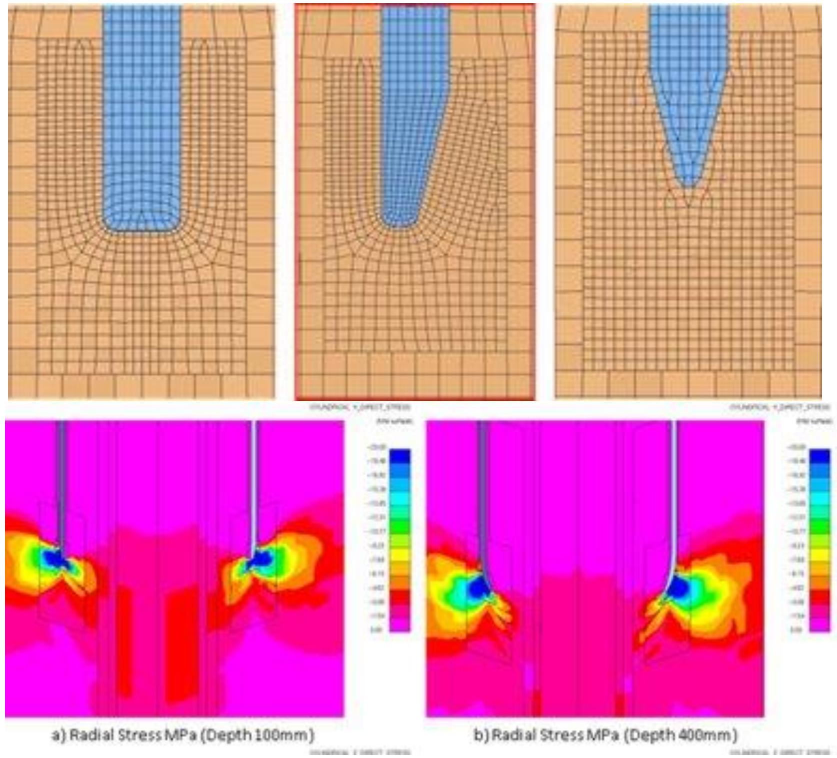
Strengthening of MP grouted connections



Validating research on large anulus grouted connections



Pile buckling during driving



Geotechnical modelling of pore pressure build up around monopiles under cyclic loading

CYCLIC DEGRADATION

Soil model development

We develop, verify and validate our own material models (in-house)

[Linear elastic]

Mohr Coulomb (all)

Brick Model (clay)

MAT-hysteretic (all)

Nor-Sand (sand)

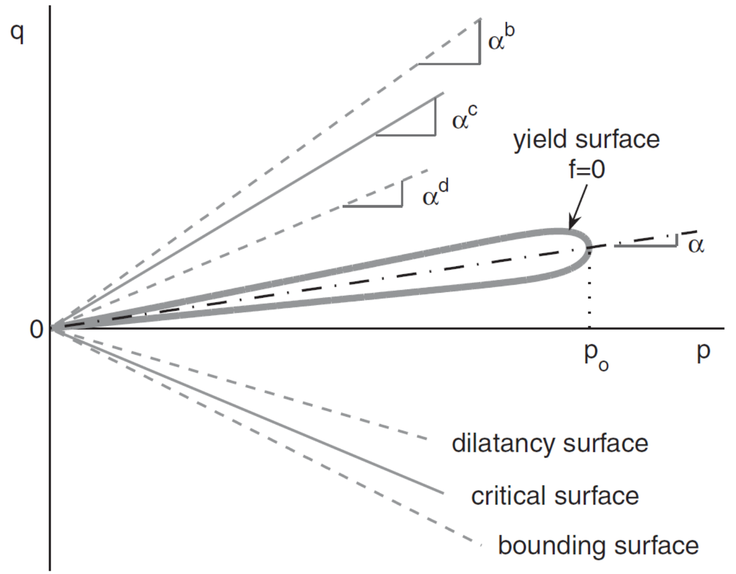
Sanisand (sand)

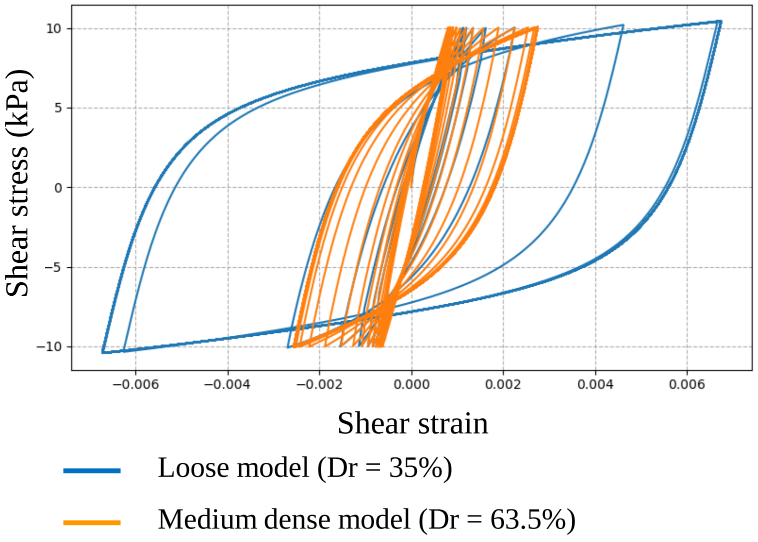
PM4Sand (sand)

Simple model

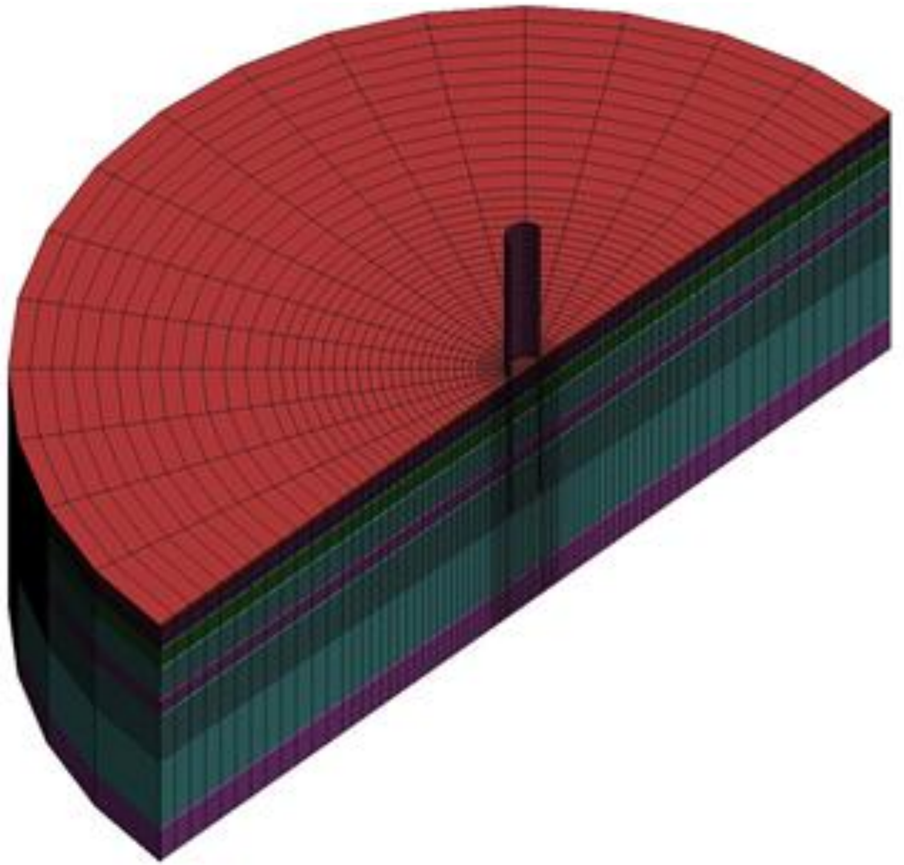
Advanced model

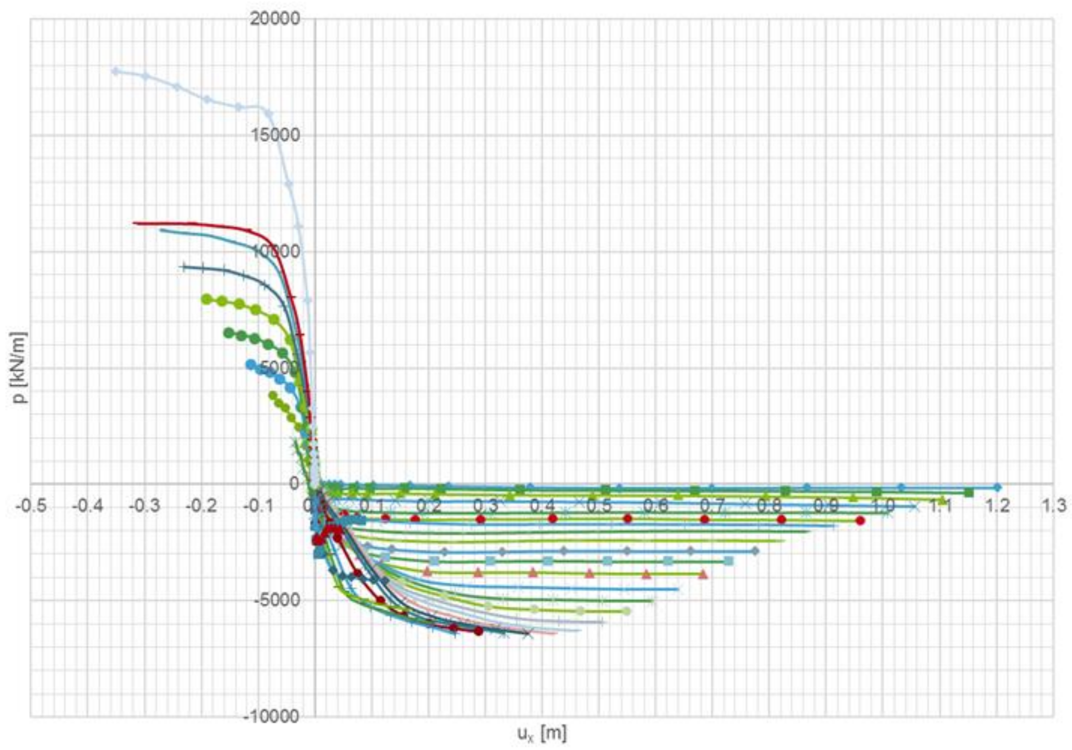
Model calibration using drained/undrained monotonic triaxial tests / undrained cyclic triaxial test





3D finite element analysis to develop nonlinear soil springs

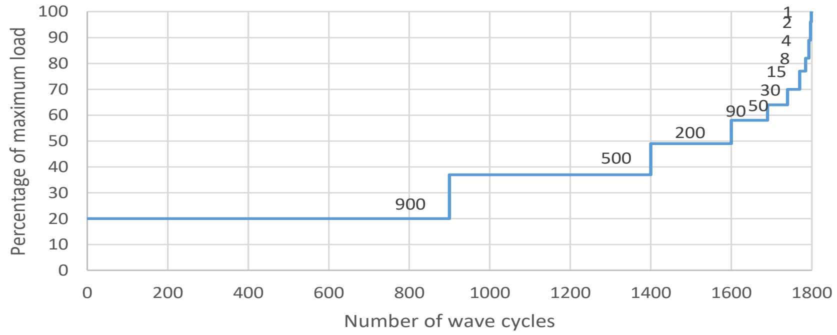


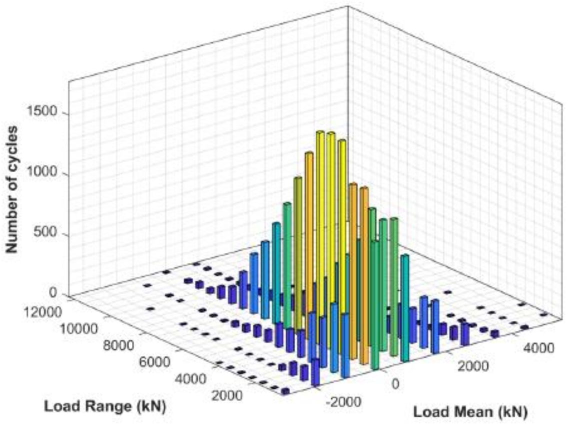


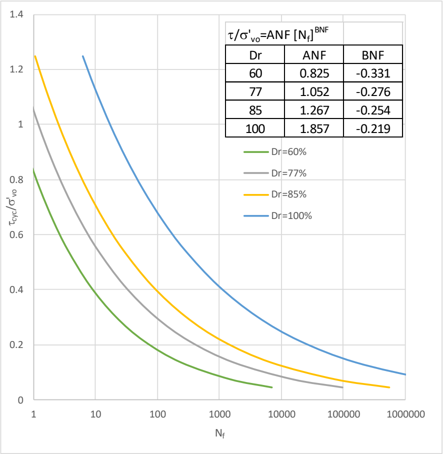
Project-specific (p-y) & (m-θ) curves

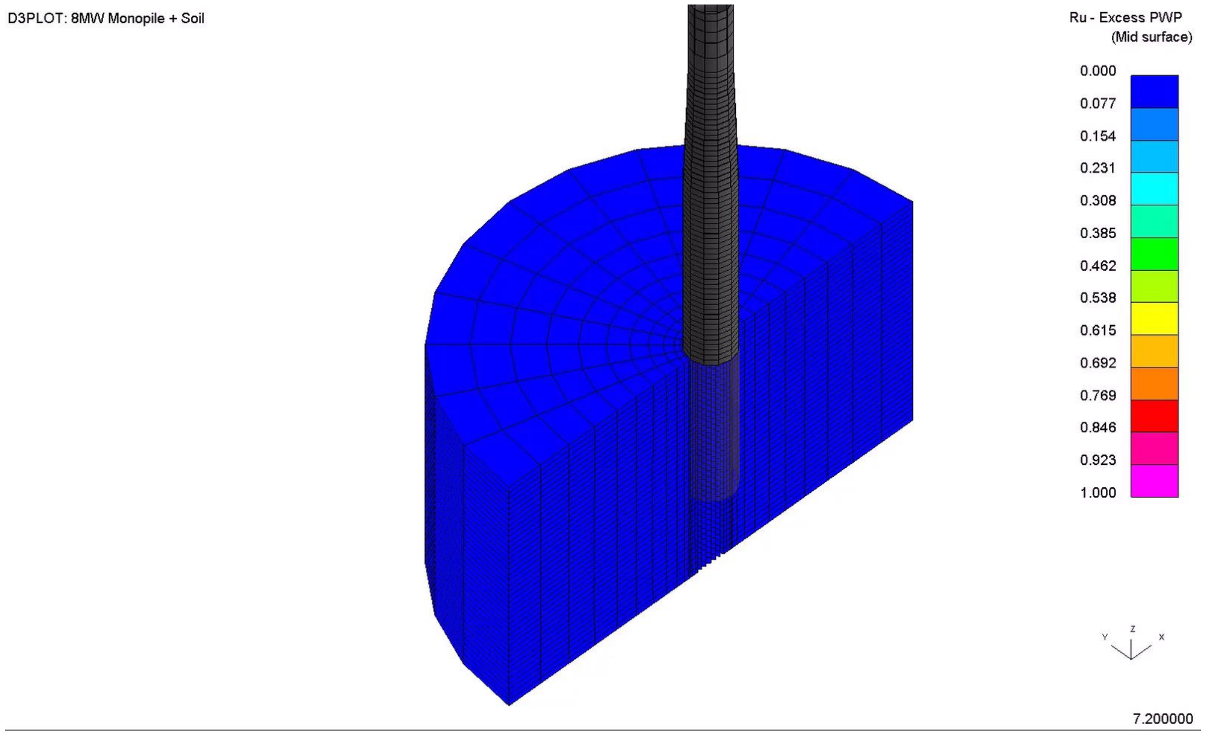
Cyclic loading of monopiles

Hansteen Storm









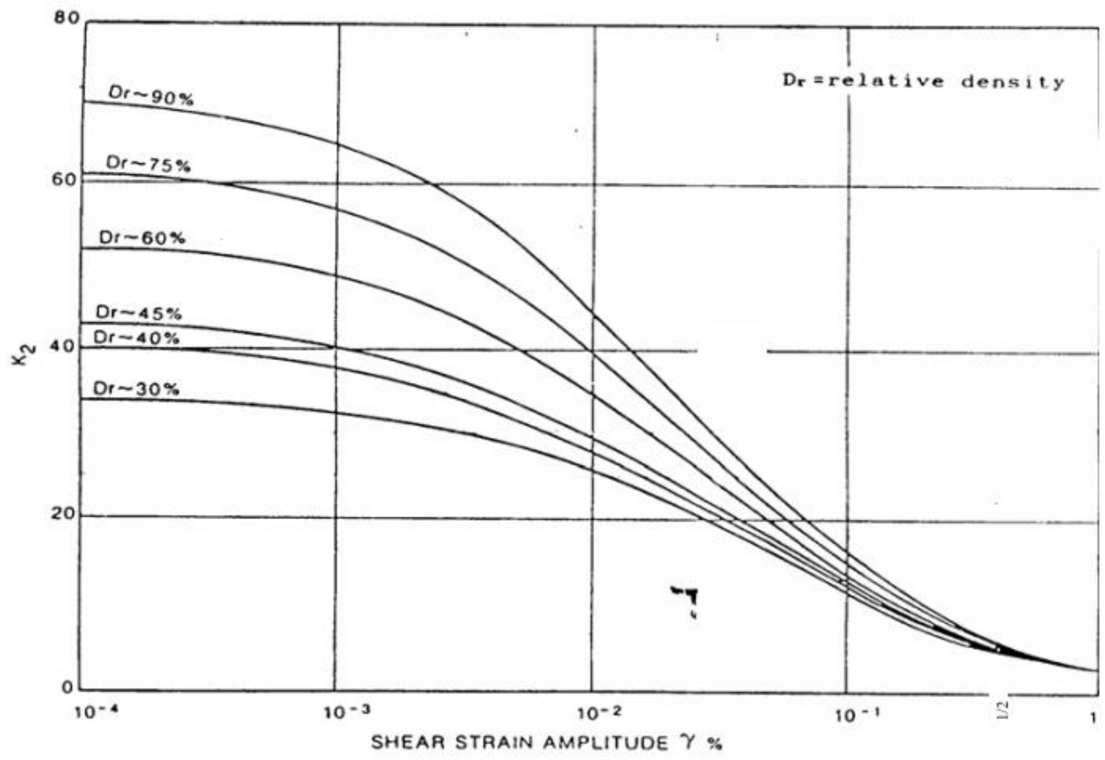
Excess pore pressure generation in soil around pile due to cyclic loading

Cyclic stiffness of soil

- Key behaviour of soil during cyclic loading: as it undergoes shear strain, its shear stiffness G_0 reduces.
- Degradation curves of G_0 vs shear strain have been suggested by various authors
- Various methodologies are available for calculating G_0, however the best methodology is that using shear wave velocity from shear wave testing.

$$G_0=\rho(v_s)^2$$

Degradation curves of G_0 vs shear strain suggested by Seed and Idriss 1970 for sands.



$$G = 220K_2(\sigma'_m)^2 \ kN/m^2 = 22K_2Pa(\frac{\sigma'_m}{Pa})^{1/2}$$

Where: Pa = Atmospheric Pressure

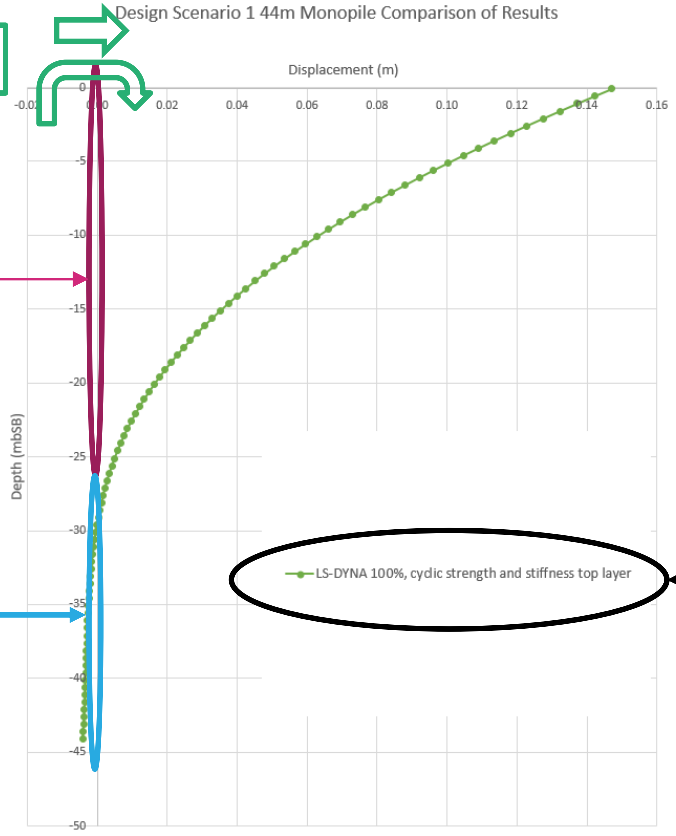
$$\sigma'_m = \frac{\sigma'_1+\sigma'_2+\sigma'_3}{3}$$

Modelling of monopiles under cyclic loading

Loads applied

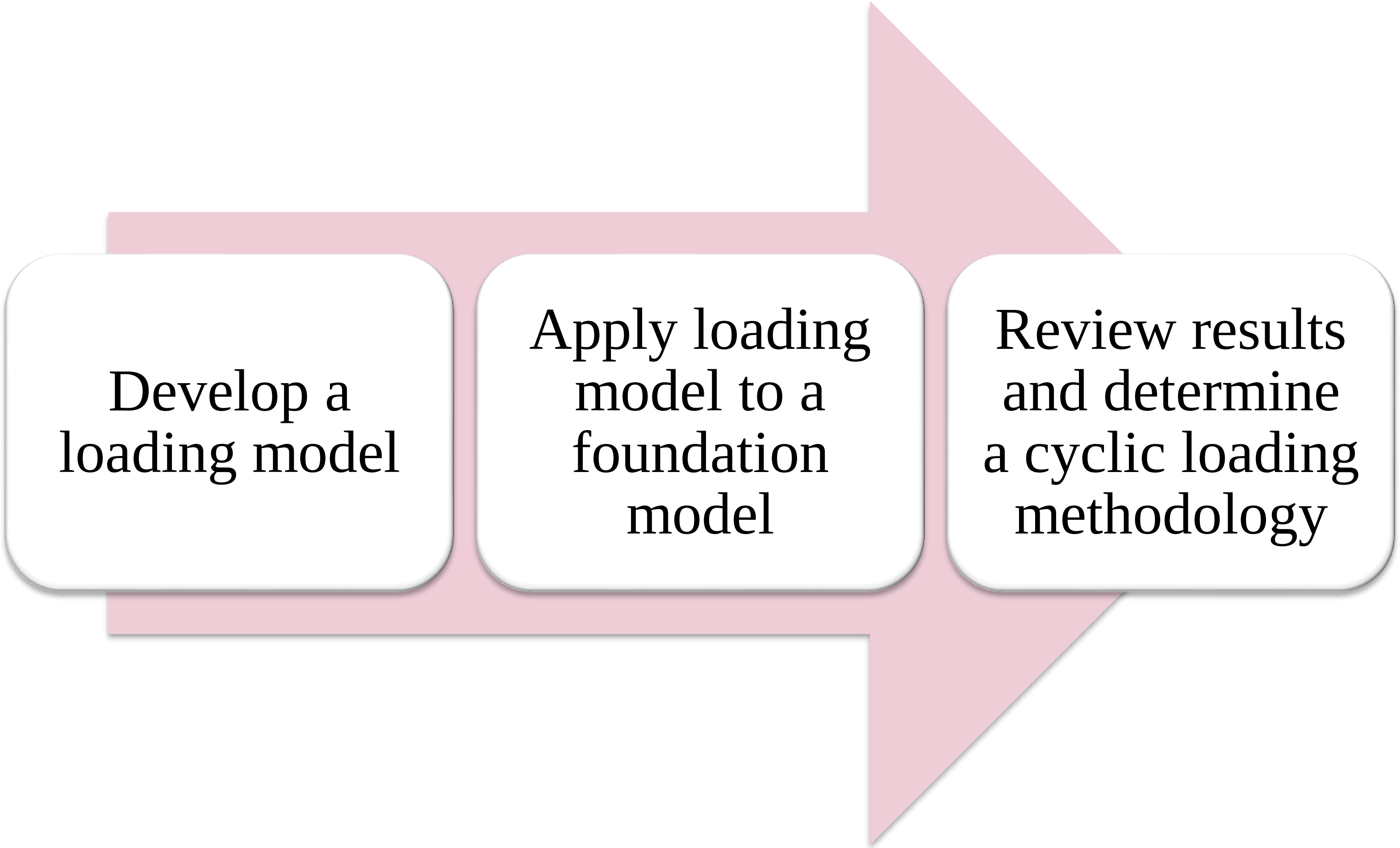
Area of high deflection: cyclic degradation taken place G_0 at ~10%?

Area of low deflection: less cyclic degradation taken place, G_0 at ~100%?



LS DYNA analysis: Finite Element Analysis (FEA) of monopile.

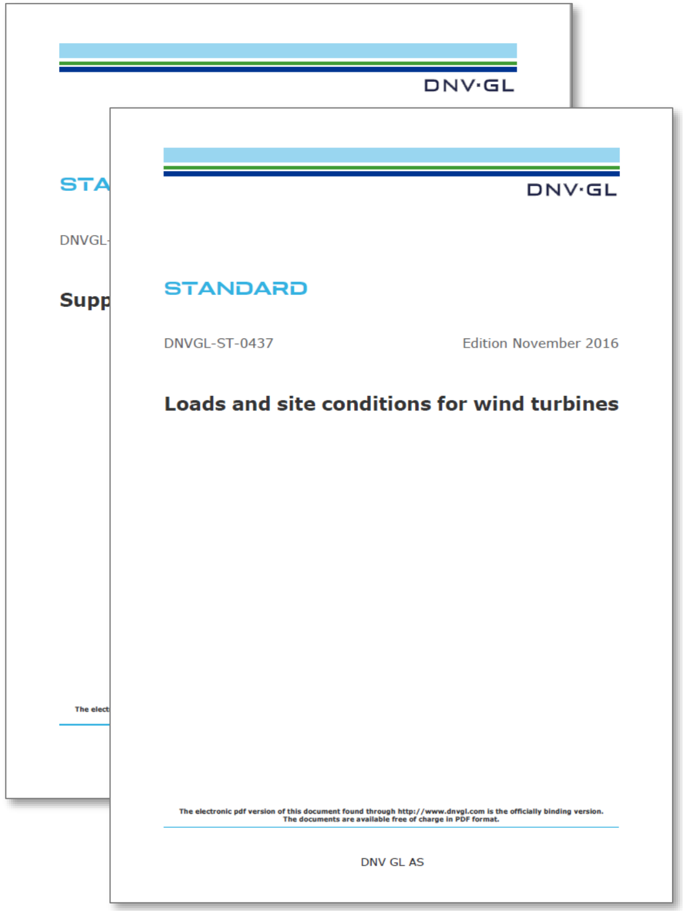
Determining cyclic degradation

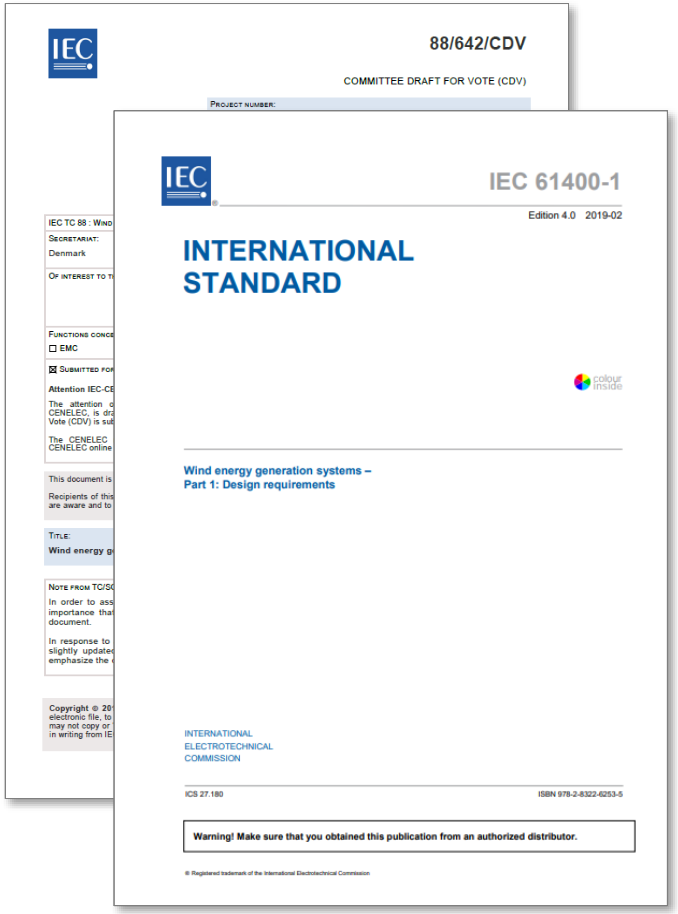


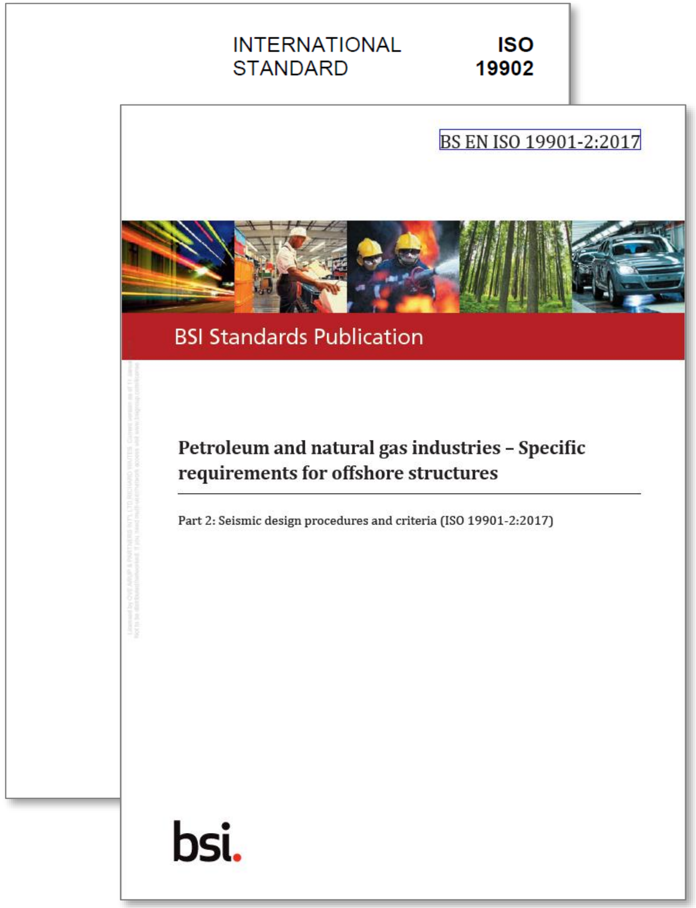
Design considerations for monopiles in seismic regions

SEISMIC DESIGN BASIS

Seismic design basis





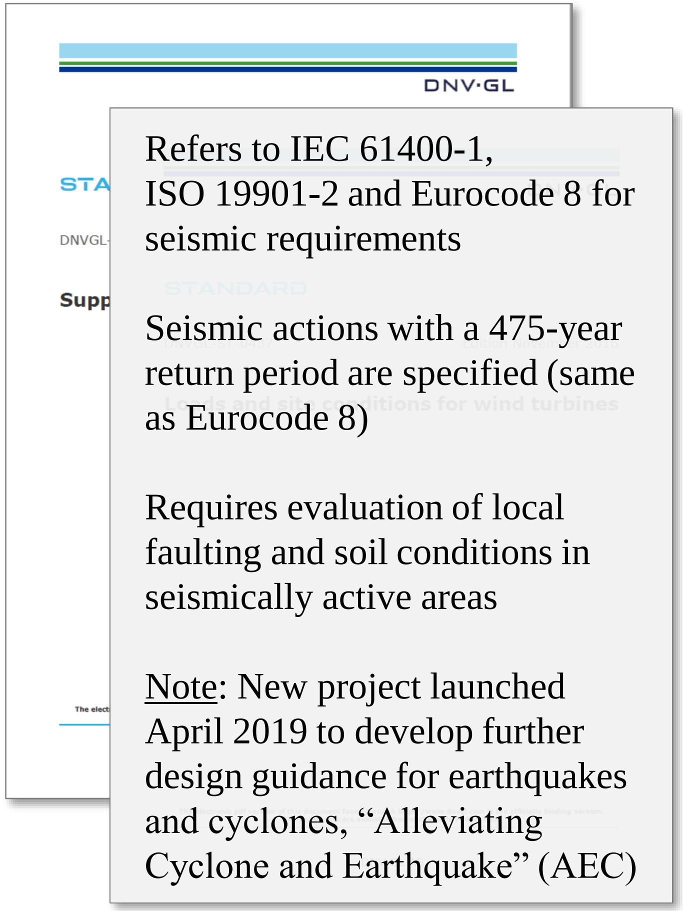


DNV-GL
Loads and site conditions for wind turbines
Support structures for wind turbines

IEC Wind energy generation systems
Part 1: Design requirements
Part 3-1: Design requirements for fixed offshore wind turbines

ISO
Seismic design procedures and criteria
Fixed steel offshore structures

Seismic design basis



Refers to IEC 61400-1, ISO 19901-2 and Eurocode 8 for seismic requirements

Seismic actions with a 475-year return period are specified (same as Eurocode 8)

Requires evaluation of local faulting and soil conditions in seismically active areas

Note: New project launched April 2019 to develop further design guidance for earthquakes and cyclones, “Alleviating Cyclone and Earthquake” (AEC)

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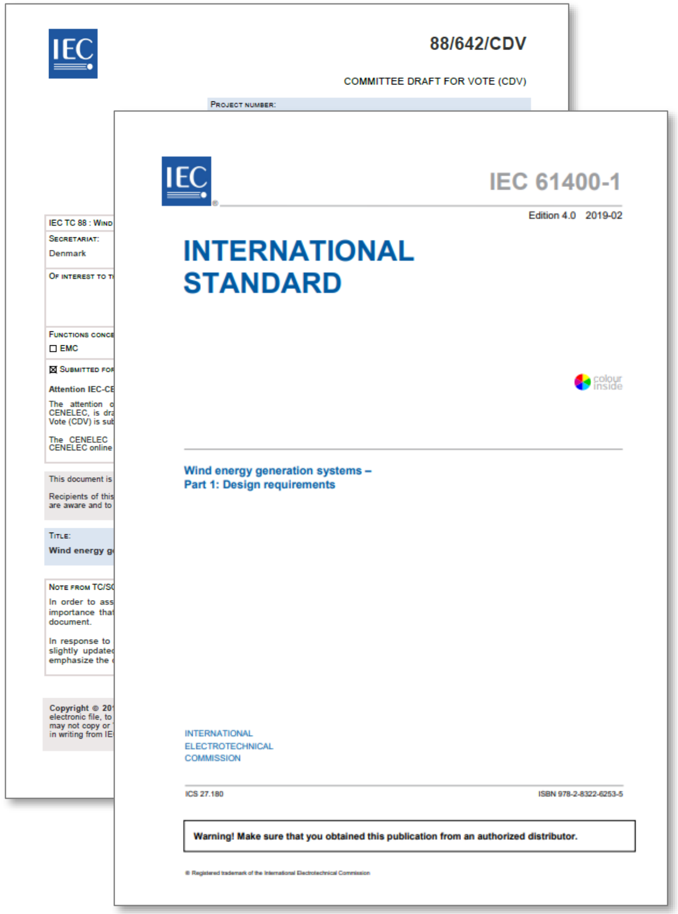
Loads and site conditions for wind turbines
Support structures for wind turbines



IEC Wind energy generation systems
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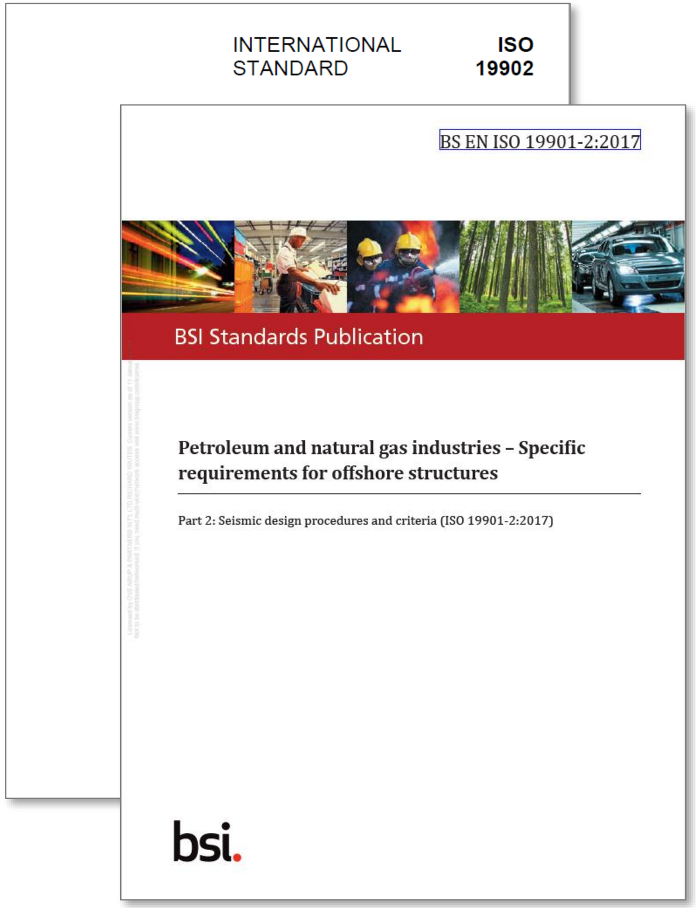

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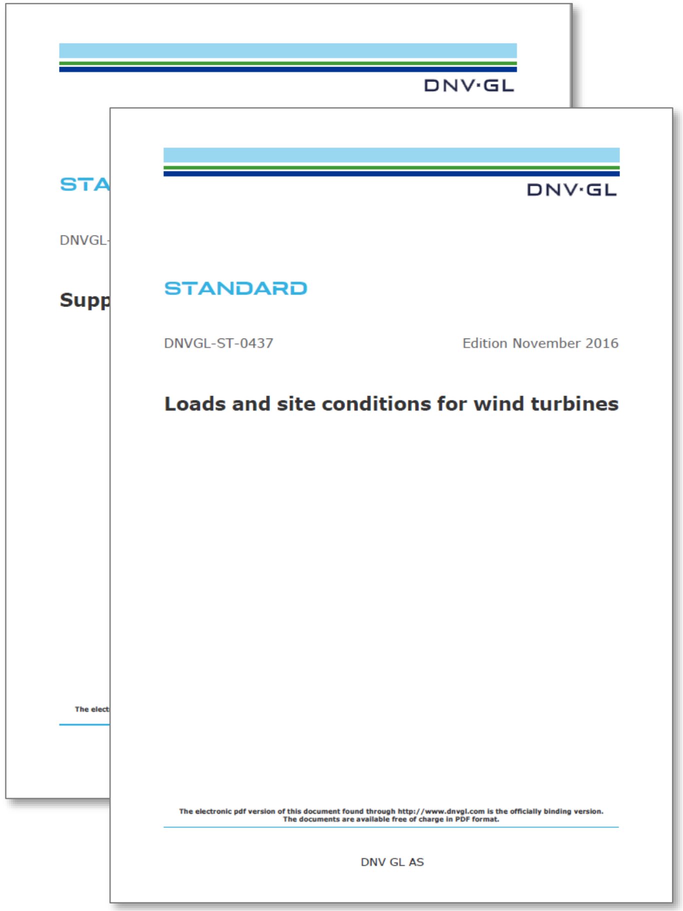
Seismic design basis


DNV·GL

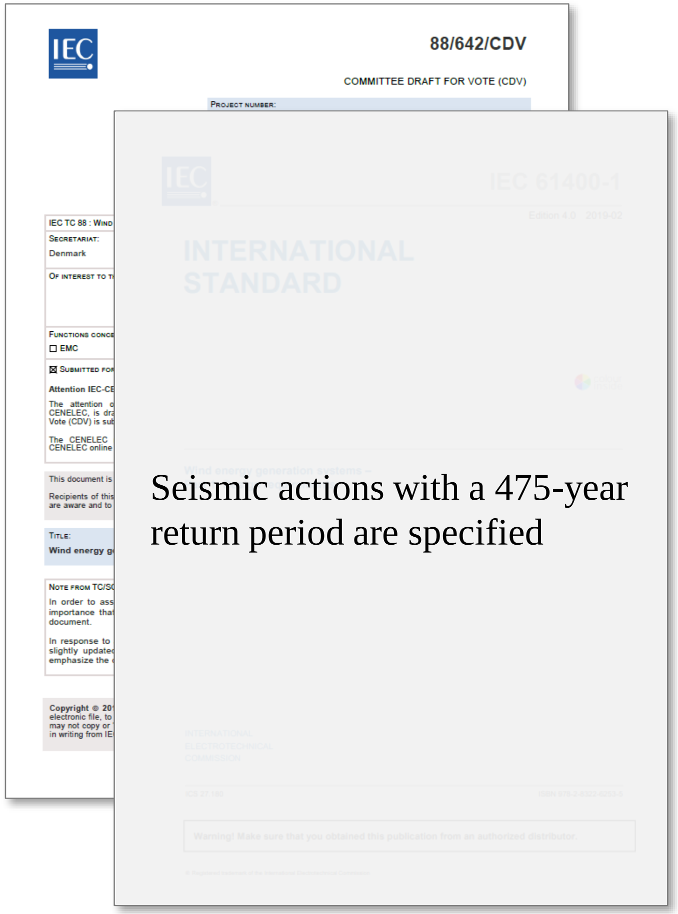
STANDARD

DNVGL-ST-0437 Edition November 2016

Loads and site conditions for wind turbines

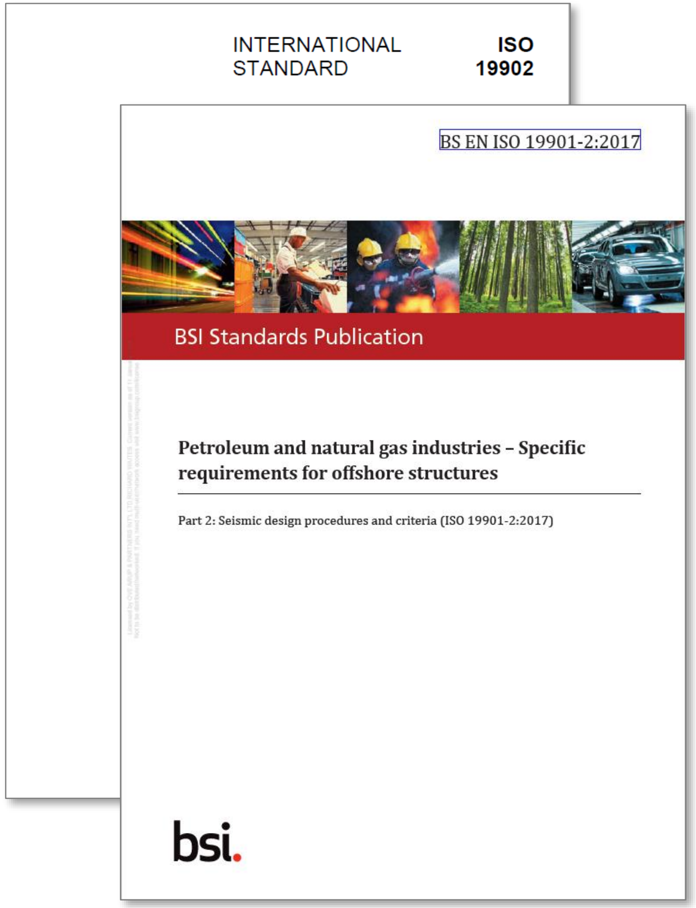
The electronic pdf version of this document found through http://www.dnvgl.com is the officially binding version. The documents are available free of charge in PDF format.

DNV GL AS


88/642/CDV

COMMITTEE DRAFT FOR VOTE (CDV)

Seismic actions with a 475-year return period are specified


INTERNATIONAL STANDARD ISO 19902

BS EN ISO 19901-2:2017

BSI Standards Publication

Petroleum and natural gas industries – Specific requirements for offshore structures

Part 2: Seismic design procedures and criteria (ISO 19901-2:2017)

bsi.

DNV-GL
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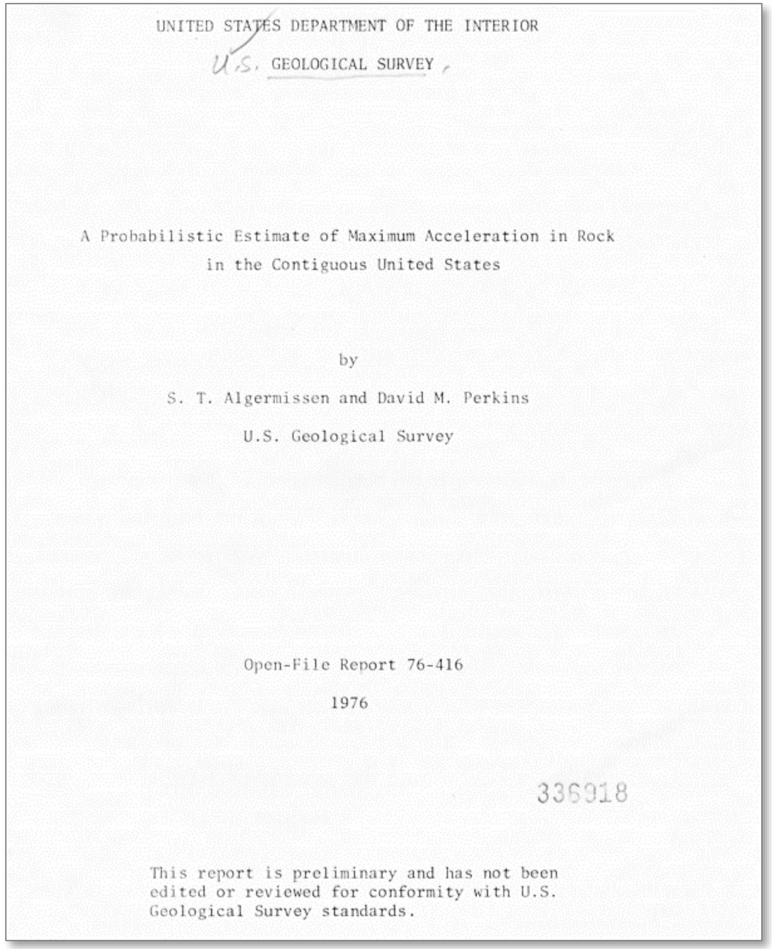

UNITED STATES DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

A Probabilistic Estimate of Maximum Acceleration in Rock
in the Contiguous United States

by

S. T. Algermissen and David M. Perkins

U.S. Geological Survey

Open-File Report 76-416

1976

336918

This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards.

Algermissen & Perkins (1976)
The first probabilistic hazard maps for the US;
Uses 475-year return period based on 50-year 'design life' and 10% probability of exceedance

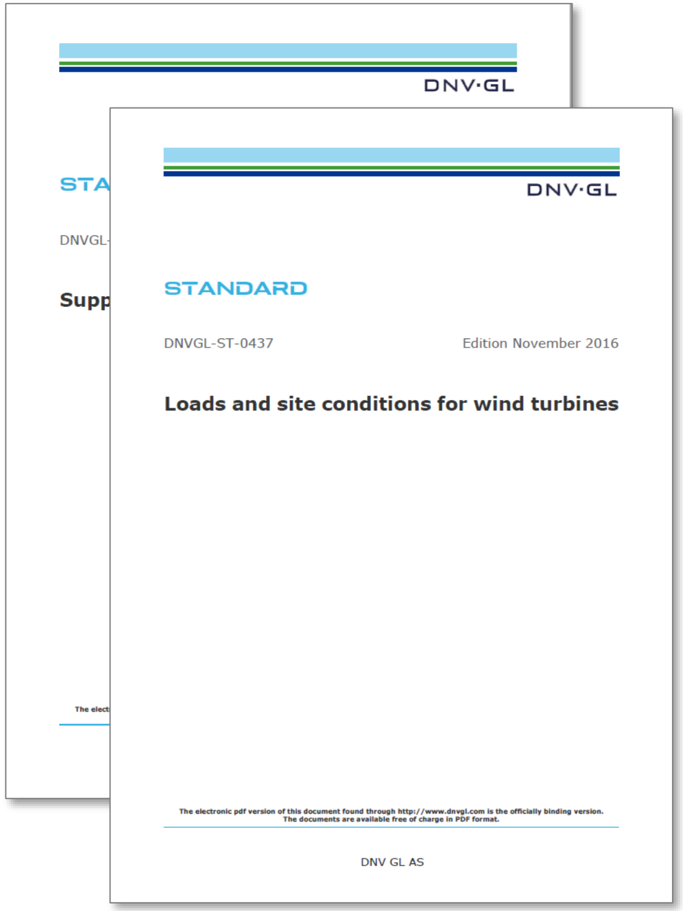
" The return period of 475 years was the result of selecting 50 years as the exposure period, although it was acknowledged that '*the use of a 50-year interval to characterize the probability is a rather arbitrary convenience, and does not imply that all buildings are thought to have a design life of 50 years*' (ATC, 1978). Algermissen and Perkins [38] stated that '*for structures which should remain operable after large, damaging earthquakes, the 10% exceedance probability in 50 years seems reasonable*', although the choice of 10% was adopted on the rather arbitrary basis of being a significance level often taken by statisticians '*to be meaningful*' [39]. "

Bommer & Pinho (2006)

i.e., the 475-year return period used in building codes all over the world, and referred to by DNV-GL and IEC standards and Eurocode 8 is:

- arbitrary
- not calibrated for use in offshore wind applications
- in building applications, associated with 'life safety' performance and heavy structural damage

Seismic design basis



DNV-GL
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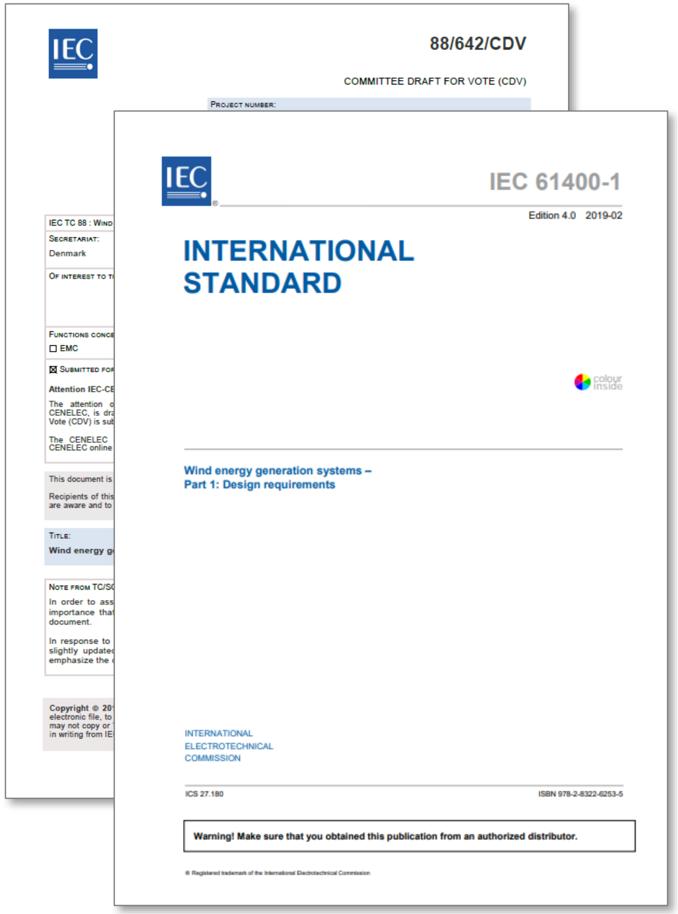
Support structures for wind turbines



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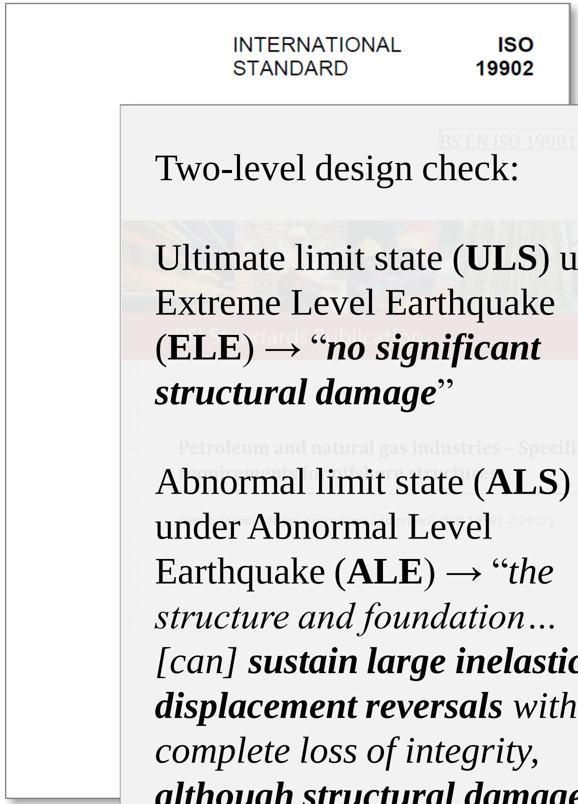
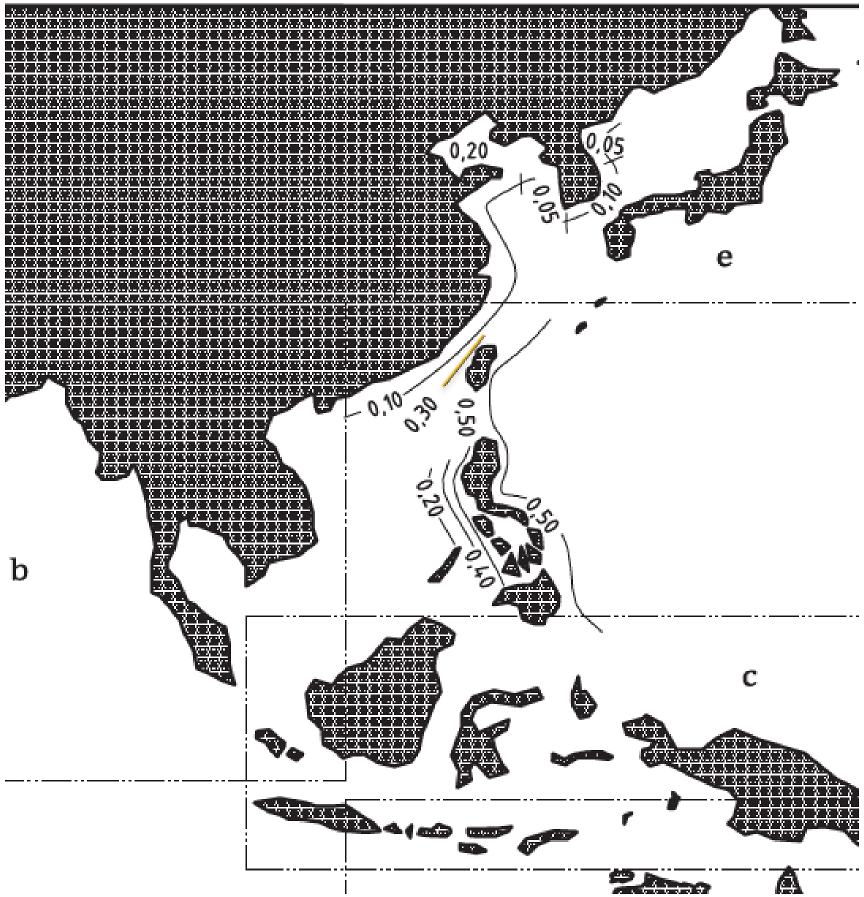


Two-level design check:

Ultimate limit state (**ULS**) under Extreme Level Earthquake (**ELE**) → "***no significant structural damage***"

Abnormal limit state (**ALS**) under Abnormal Level Earthquake (**ALE**) → "*the structure and foundation… [can]* ***sustain large inelastic displacement reversals*** *without complete loss of integrity,* ***although structural damage can occur***"

ISO
Seismic design procedures and criteria
Fixed steel offshore structures



ISO 19901-2: Seismic design requirements based on seismic risk

Table 1 — Site seismic zone

$S_{a,map}(1,0)$	<0,03 g	0,03 g to 0,10 g	0,11 g to 0,25 g	0,26 g to 0,45 g	>0,45 g
Seismic zone	0	1	2	3	4

Table 2 — Target annual probability of failure, P_f

Exposure level	P_f
L1	4×10^{-4} = 1/2 500
L2	1×10^{-3} = 1/1 000
L3	$2,5 \times 10^{-3}$ = 1/400

"high environmental and/or economic consequences"

Table 3 — Seismic risk category, SRC

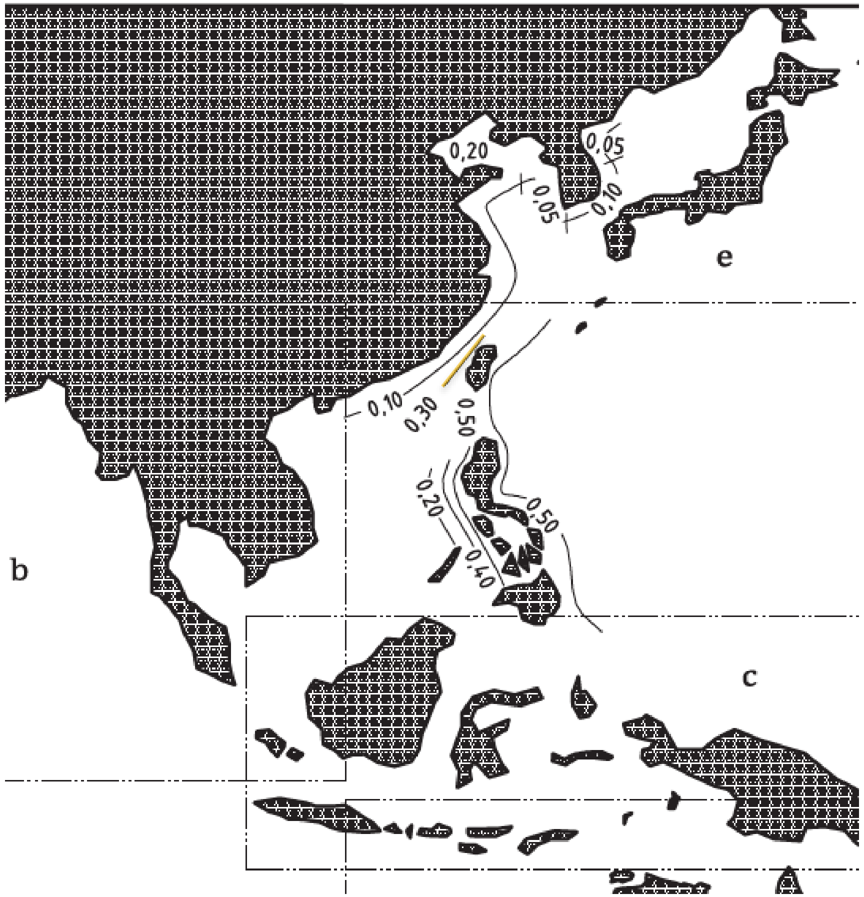
Site seismic zone	Exposure level		
	L1	L2	L3
0	SRC 1	SRC 1	SRC 1
1	SRC 3	SRC 2	SRC 2
2	SRC 4	SRC 2	SRC 2
3	SRC 4	SRC 3	SRC 2
4	SRC 4	SRC 4	SRC 3

Table 4 — Seismic design requirements

SRC	Seismic action procedure	Evaluation of seismic activity	Non-linear ALE analysis
1	None	None	None
2	Simplified	ISO maps or regional maps	Permitted
3[a]	Simplified	Site-specific, ISO maps or regional maps	Recommended
	Detailed	Site-specific	Recommended
4	Detailed	Site-specific	Required

Non-linear finite element analysis

Probabilistic seismic hazard assessment (PSHA)



Abnormal Level Earthquake (ALE) based on target annual probability of failure.

For exposure level L1, typically ALE ~ 3000–4000 years

Extreme Level Earthquake (ELE) evaluated based on the anticipated margin between "*little or no damage*" and "*major failure*" – around 2.0 for monopile design and up to 2.8 for jacket design; requires nonlinear analysis to calibrate.

Therefore, L1 typically ELE ~ 400–800 years (monopiles)

→ ISO 19901-2 design anchored on life safety ALE check – appropriate for offshore oil & gas applications but less relevant for offshore wind.

Design considerations for monopiles in seismic regions

RESEARCH & DEVELOPMENT MONOPILE WITH LIQUEFIABLE SOILS

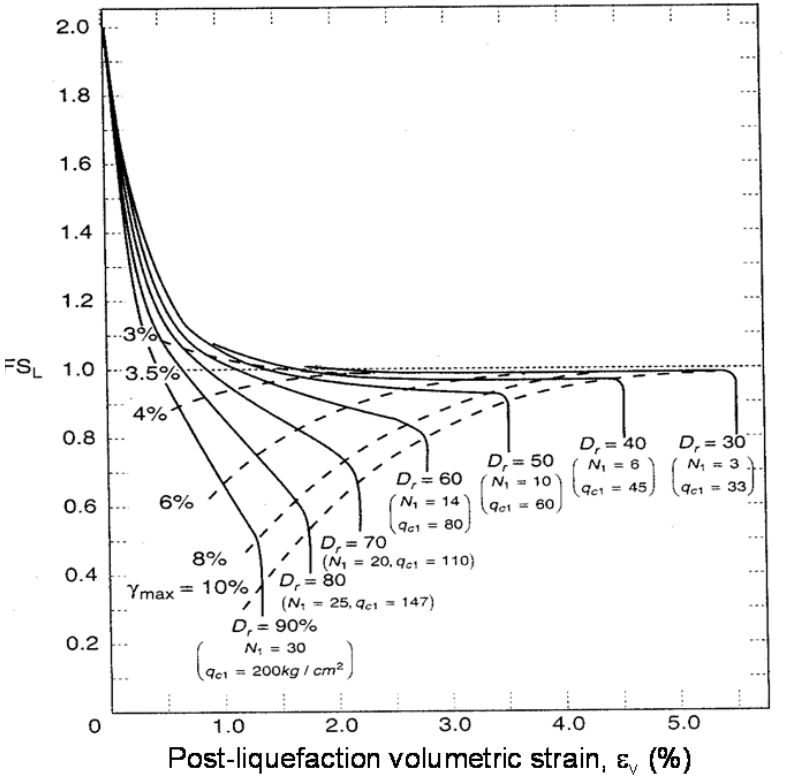
Evaluation of liquefaction potential

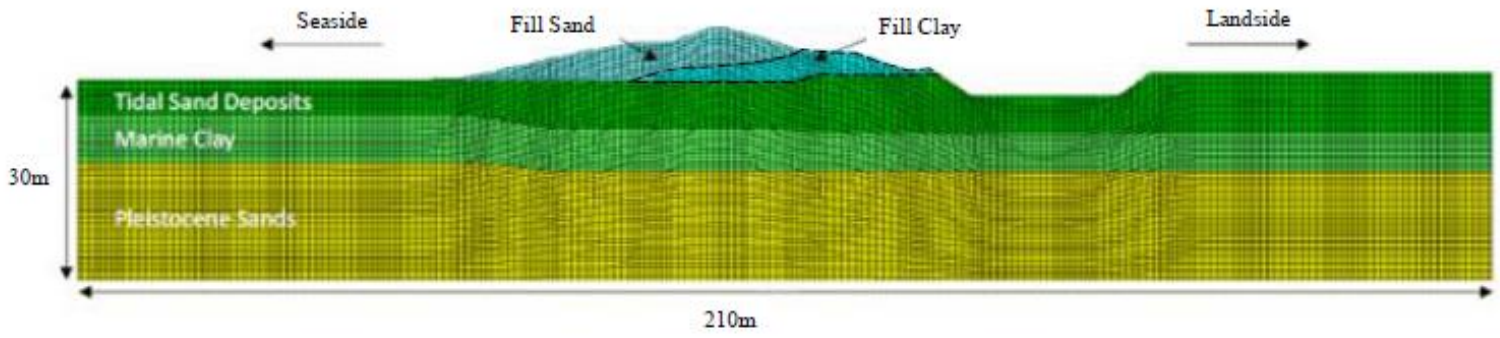
$$FS = \frac{\text{CAPACITY}}{\text{DEMAND}} = \frac{\text{Cyclic resistance ratio (CRR)}}{\text{Cyclic stress ratio (CSR)}}$$

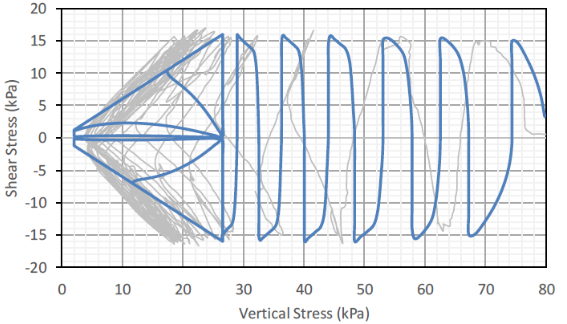
FS >> 1 Liquefaction unlikely, all good

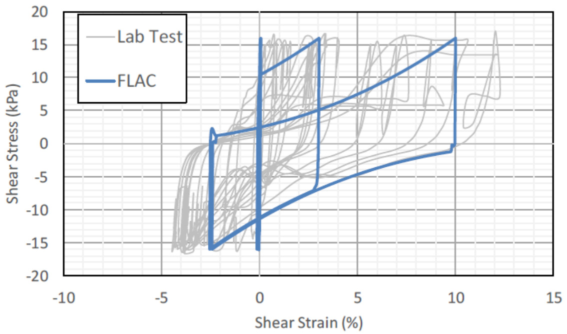
FS < 1 Liquefaction probable, what next?

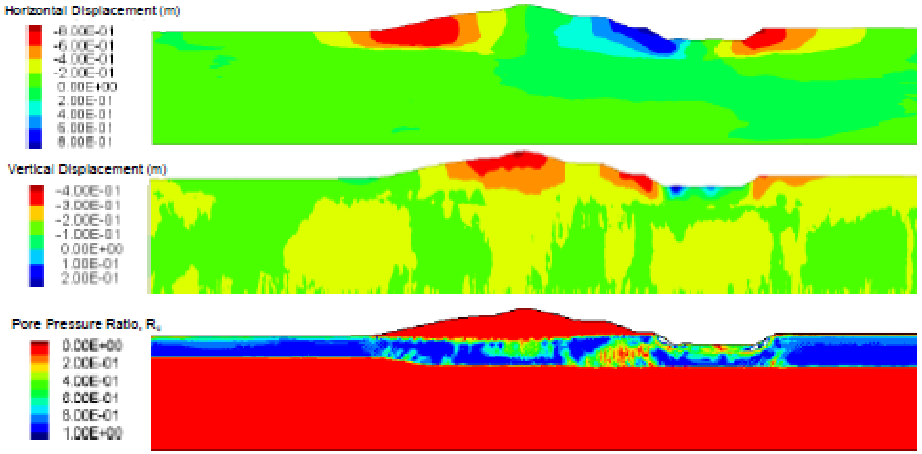
Dyke stability



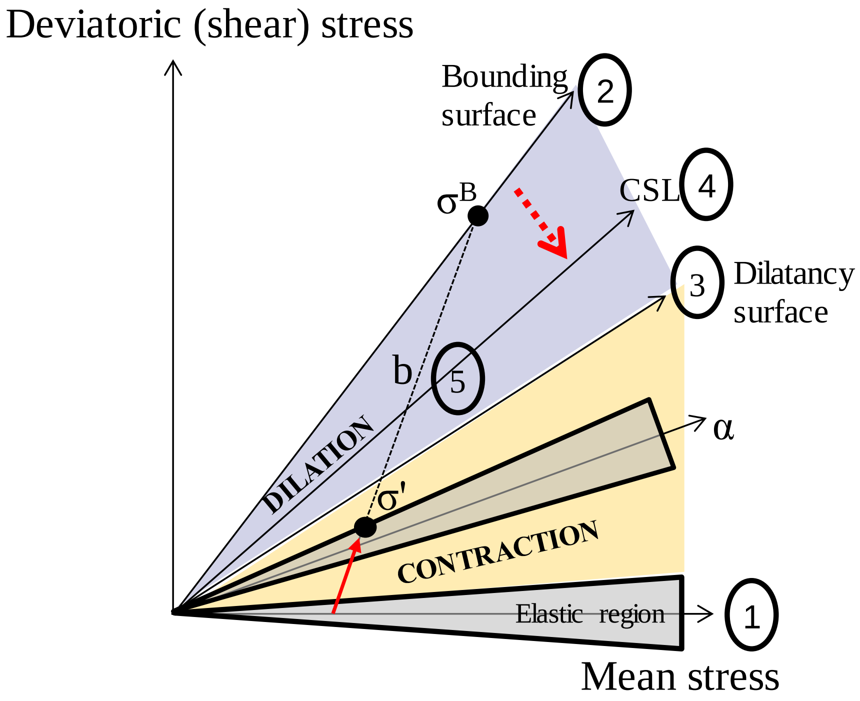








Validation of constitutive model - SANISAND



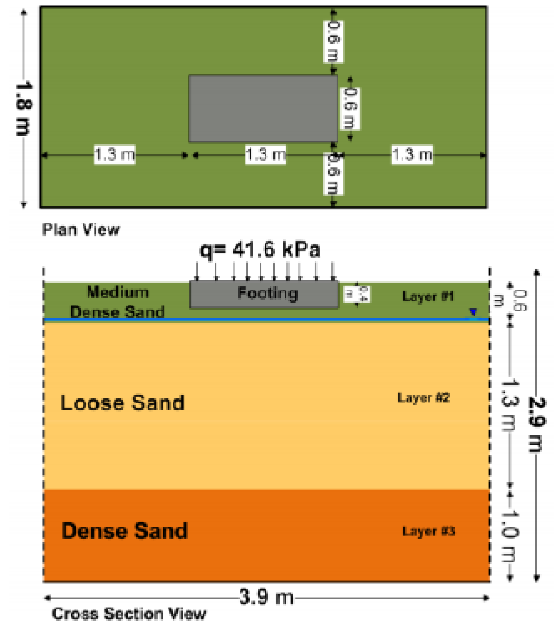
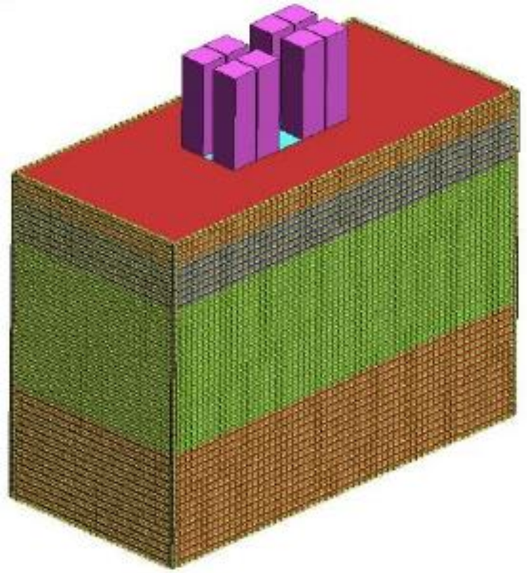
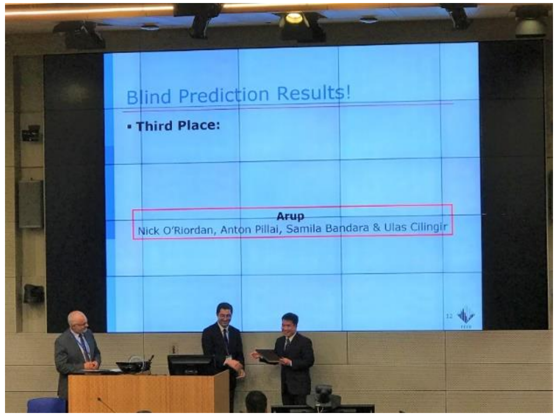


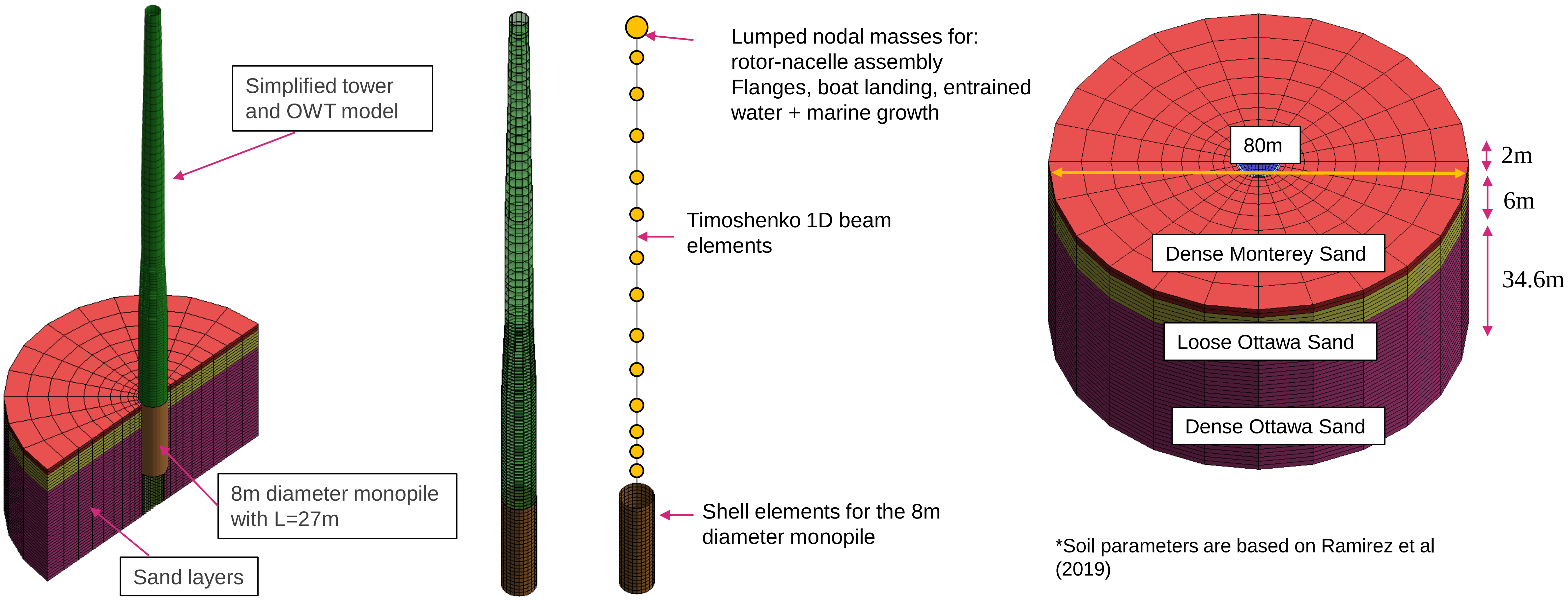
Fig. 1: Model ground configuration





Based on the works by Dafalias & Manzari (2004), Dafalias, Papadimitriou and Xiang (2004) and Taiebat and Dafalias (2008)

Dynamic soil-structure interaction of monopiles in liquefiable sands



*Soil parameters are based on Ramirez et al (2019)

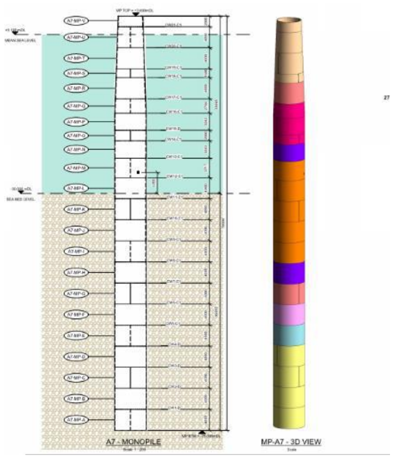
To finish - detailed design of monopile foundations

Using automated design procedures to deliver efficient design

‘A Port’ offshore wind farm

Detailed design of the first wind farm in Japanese waters to achieve design certification. Also the first offshore wind farm to be constructed in a highly seismic zone.

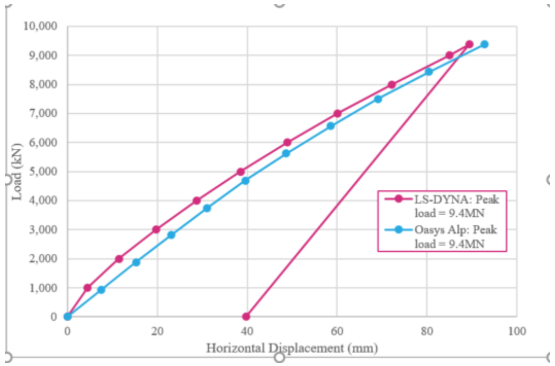
- 33 No. Foundations
- 4.2 MW WTGs
- 5.5m MPs with conical grouted connections



‘K Port’ offshore wind farm

Detailed design of the second wind farm in Japanese waters:

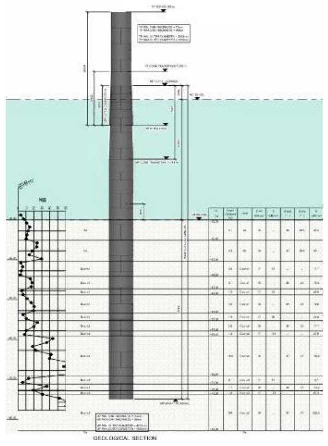
- 36 No. Foundations
- 5.2 MW WTGs
- 6.5m MPs with bolted flange connection



‘Y Port’ offshore wind farm

FEED design of the first XL monopile wind farm in Japanese waters:

- 70 No. Foundations
- 9.52 MW WTGs
- 9m MPs with bolted flange connection



ARUP

SHAPE A BETTER WORLD

Thank you!